Open and hidden charm states as dynamically generated resonances

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-- Unitary chiral approach to meson meson interaction
-- Meson-meson and meson-vector meson interaction with charmed mesons
-- Open and hidden charm scalar resonances
-- Open and hidden charm axial vector resonances

General scheme *Oller, Meissner PL '01* (meson baryon as exemple)

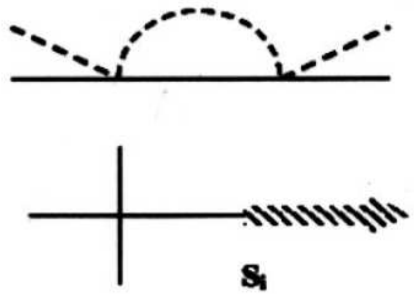
- **Unitarity** in coupled channels $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Sigma$, $\eta\Lambda$, $K\Xi$, in $S=-1$

$$\begin{aligned}
\mathrm{Im}T_{ij} &= T_{il}\sigma_{ll}T^{*}_{lj} \\
\sigma_l &\equiv \sigma_{ll} \equiv \frac{2Mq_l}{8\pi\sqrt{s}} \\
\sigma &= -\mathrm{Im}T^{-1}
\end{aligned}$$

\- Dispersion relation

$$\begin{aligned}
T^{-1}_{ij} &= -\delta_{ij}\left\{\hat{a}_i(s_0)+\frac{s-s_0}{\pi}\int_{s_i}^{\infty}ds'\frac{\sigma(s')_i}{(s-s')(s'-s_0)}\right\}+ \\
&+ \; V^{-1}_{ij} \equiv -g(s)_i\delta_{ij}+V^{-1}_{ij}
\end{aligned}$$

g(s) accounts for the right hand cut



V accounts for local terms, pole terms and crossed dynamics. V is determined by matching the general result to the χPT expressions (usually at one loop level)

$$g(s) = \frac{2M_i}{16\pi^2}\left\{a_i(\mu) + \log\frac{m_i^2}{\mu^2} + \frac{M_i^2 - m_i^2 + s}{2s}\log\frac{M_i^2}{m_i^2} + \right.$$
$$\left. + \frac{q_i}{\sqrt{s}}\log\frac{m_i^2 + M_i^2 - s - 2q_i\sqrt{s}}{m_i^2 + M_i^2 - s + 2q_i\sqrt{s}}\right\}$$

μ regularization mass

a_i subtraction constant

Inverting T^{-1}:

$$T = [1 - Vg]^{-1}V$$

Example 1: Take $V \equiv$ lowest order chiral amplitude

In meson-baryon S-wave

$$[1 - V\, g]\, T = V \to T = V + V\, g\, T$$

Bethe Salpeter eqn. with kernel V

This is the method of *E. O., Ramos '98* using cut off to regularize the loops

Oller, Meissner show equivalence of methods with

$$a_i(\mu) \simeq -2 \ln \left[1 - \sqrt{1 + \frac{m_i^2}{\mu^2}}\right] ;$$

μ cut off

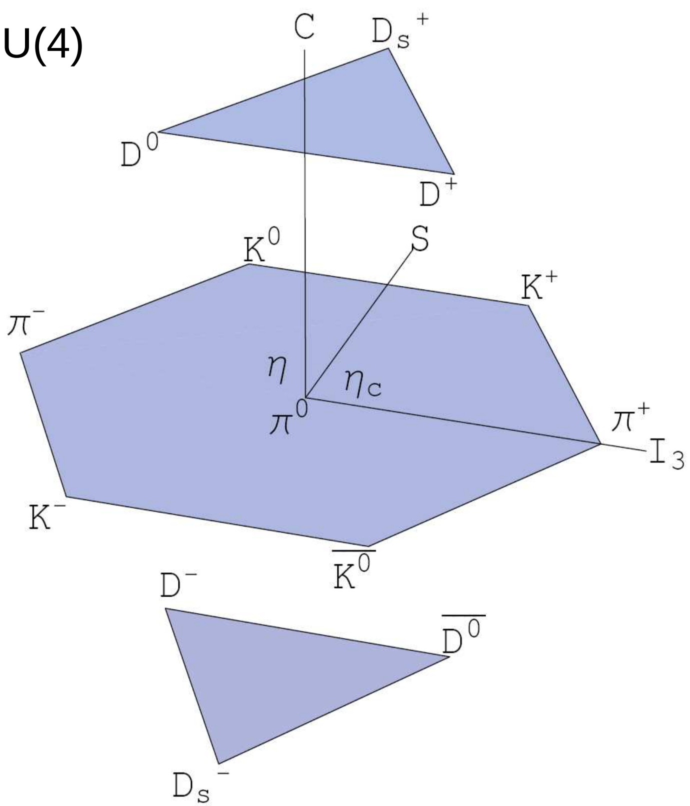
$a_i \simeq -2 \to \mu \simeq 630$ MeV in $\bar{K}N$

If higher order Lagrangians not well determined then fit a_i to the data

Dynamically Generated Open and Hidden Charm Meson Systems

D. Gamermann, E. O:, D. Strottman, M.J. Vicente Vacas, Phys. Rev D

15 plet of SU(4)



Pseudoscalar meson – Pseudoscalar meson interaction

charm	Interacting multiplets
2	$\bar{3} \otimes \bar{3} \rightarrow 3 \oplus \bar{6}$
1	$\bar{3} \otimes 8 \rightarrow \overline{15} \oplus \bar{3} \oplus 6$ $\bar{3} \otimes 1 \rightarrow \bar{3}$
0	$\bar{3} \otimes 3 \rightarrow 8 \oplus 1$ $1 \otimes 1 \rightarrow 1$ $8 \otimes 1 \rightarrow 8$ $8 \otimes 8 \rightarrow 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$

Meson Meson chiral Lagrangian in SU(3)

$$\mathcal{L}_\chi = \frac{f_\pi^2}{4} Tr\left(\partial_\mu U \partial^\mu U\right) + \frac{f_\pi^2 m_\pi^2}{4} Tr\left(U + U^\dagger - 2\right)$$

$$U = e^{\frac{i\sqrt{2}\phi_8}{f_\pi}}$$

$$\phi_8 = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & \frac{-2\eta}{\sqrt{6}} \end{pmatrix}$$

$$J_\mu = [\partial_\mu \Phi, \Phi]$$

$$\mathcal{L}_{PPPP} = \frac{1}{12 f^2} Tr(J_\mu J^\mu + \Phi^4 M)$$

$$\Phi = \sum_{i=1}^{15} \frac{\varphi_i}{\sqrt{2}} \lambda_i =$$

SU(4) generalization

$$= \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & K^0 & D^- \\ K^- & \bar{K}^0 & \frac{-2\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & D_s^- \\ D^0 & D^+ & D_s^+ & \frac{-3\eta_c}{\sqrt{12}} \end{pmatrix}$$

$$M = \begin{pmatrix} m_\pi^2 & 0 & 0 & 0 \\ 0 & m_\pi^2 & 0 & 0 \\ 0 & 0 & 2m_K^2 - m_\pi^2 & 0 \\ 0 & 0 & 0 & 2m_D^2 - m_\pi^2 \end{pmatrix} \qquad \Phi = \begin{pmatrix} \phi_8 + \frac{1}{\sqrt{12}}\phi_1 \hat{1}_3 & \phi_3 \\ \phi_{\bar{3}} & -\frac{3}{\sqrt{12}}\phi_1 \end{pmatrix}$$

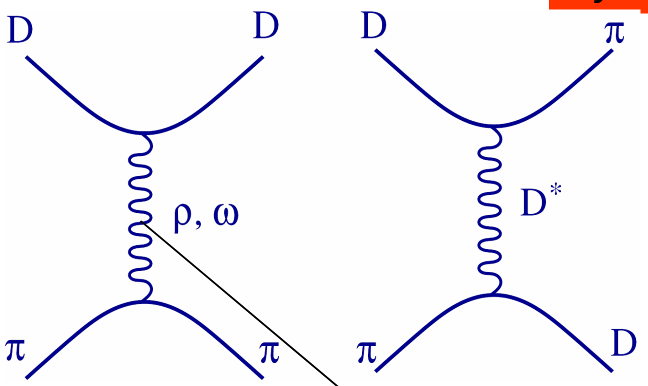
$$\mathcal{L}_{PPPP} = \frac{1}{12f^2}(\mathcal{L}_8 + \mathcal{L}_3 + \mathcal{L}_{31} + \mathcal{L}_{83} + \mathcal{L}_{831} + \mathcal{L}_{mass})$$

$$\begin{aligned} \phi_8 &= \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & \frac{-2\eta}{\sqrt{6}} \end{pmatrix} \\ \phi_3 &= \begin{pmatrix} \bar{D}^0 \\ D^- \\ D_s^- \end{pmatrix} \\ \phi_{\bar{3}} &= \begin{pmatrix} D^0 & D^+ & D_s^+ \end{pmatrix} \\ \phi_1 &= \eta_c \end{aligned}$$

$$\begin{aligned} \mathcal{L}_8 &= Tr\left(J_{88\mu}J_{88}^\mu\right) \\ \mathcal{L}_3 &= J_{\bar{3}3\mu}J_{\bar{3}3}^\mu + Tr\left(J_{3\bar{3}\mu}J_{3\bar{3}}^\mu\right) \\ \mathcal{L}_{31} &= \frac{8}{3}J_{\bar{3}1\mu}J_{13}^\mu \\ \mathcal{L}_{83} &= 2\left(J_{\bar{3}8\mu}J_{83}^\mu + Tr\left(J_{3\bar{3}\mu}J_{88}^\mu\right)\right) \\ \mathcal{L}_{831} &= \frac{4}{\sqrt{3}}\left(J_{\bar{3}1\mu}J_{83}^\mu + J_{\bar{3}8\mu}J_{13}^\mu\right) \\ \mathcal{L}_{mass} &= Tr\left(M\Phi^4\right) \end{aligned}$$

Crossed terms considered
by us, they involve exchange
of heavy vectors and are suppressed
by the large mass of charmed vectors.

$$\gamma = \left(\frac{m_L}{m_H}\right)^2$$
$$\psi_3 = \frac{1}{3} + \frac{2}{3}\left(\frac{m_L}{m_{J/\psi}}\right)^2$$
$$\psi_5 = -\frac{1}{3} + \frac{4}{3}\left(\frac{m_L}{m_{J/\psi}}\right)^2$$



Terms considered
by Kolomeitsev et al
and Chiang et al.

$$\mathcal{L}_{PPV} = -\frac{ig}{\sqrt{2}} Tr\left([\partial_\mu \Phi, \Phi] V^\mu\right)$$

$$\mathcal{L} = \frac{1}{12f^2}\left(Tr\left(J_{88\mu}J^\mu_{88} + 2J_{3\bar{3}\mu}J^\mu_{88} + J_{3\bar{3}_\mu}J^\mu_{3\bar{3}}\right) + \frac{8}{3}\gamma J_{\bar{3}1\mu}J^\mu_{13} + \frac{4}{\sqrt{3}}\gamma\left(J_{\bar{3}1\mu}J^\mu_{83} + J_{\bar{3}8\mu}J^\mu_{13}\right) + 2\gamma J_{\bar{3}8\mu}J^\mu_{83} + \psi_5 J_{\bar{3}3_\mu}J^\mu_{\bar{3}3} + \mathcal{L}_{mass}\right)$$

Experimental situation of scalar mesons

Resonance ID	C	S	I	Mass (MeV)	Γ (MeV)
f_0	0	0	0	980±10	40-100
σ	0	0	0	400-1200	250-500
a_0	0	0	1	984.7±1.2	50-100
κ	0	1	$\frac{1}{2}$	$841 \pm 30^{+81}_{-73}$	$618 \pm 90^{+96}_{-144}$
$D^*_{s0}(2317)$	1	1	0	2317.3±0.4±0.8	< 4.6
$D^*_0(2400)$	1	0	$\frac{1}{2}$	2403±14±35 2352±50	283±24±34 261±50

Resonance ID	C	S	I	RE($\sqrt{s}$) (MeV)	IM($\sqrt{s}$) (MeV)
f_0	0	0	0	918.45	-18.76
σ	0	0	0	616.19	-143.77
(?)	0	0	0	3718.93	-0.06
a_0	0	0	1	987.68	-38.29
κ	0	1	$\frac{1}{2}$	831.58	-147.24
$D^*_{s0}(2317)$	1	1	0	2317.25	0
$D^*_0(2400)$	1	0	$\frac{1}{2}$	2129.26	-157.00
(?)	1	0	$\frac{1}{2}$	2694.69	-441.89
(?)	1	1	1	2704.31	-459.50
(?)	1	-1	0	2709.39	-445.73

Table 4: Pole positions for the phenomenological model

Predicted here not yet observed

Also predicted by Kolomeitsev and Chiang, but with very narrow width.

The use of different f_pi and f_D is responsible in large part for the large widths.

Resonance ID	C	S	I	RE($\sqrt{s}$) (MeV)	IM($\sqrt{s}$) (MeV)
$D^*_{s0}(2317)$	1	1	0	2316 ± 39	0
$D^*_0(2400)$	1	0	$\frac{1}{2}$	2168 ± 48	-206 ± 74
(?)	1	0	$\frac{1}{2}$	2727 ± 39	-509 ± 71
(?)	1	1	1	2737 ± 40	-529 ± 70
(?)	1	-1	0	2721 ± 38	-500 ± 74
(?)	0	0	0	3698 ± 35	-0.10 ± 0.06

Results for the couplings to channels

Channel	f_0 (GeV)	σ (GeV)	Heavy Singlet (GeV)
$\pi\pi$	1.37	3.00	0.16±0.05
$K\bar{K}$	3.80	1.25	0.05±0.03
$\eta\eta$	3.14	0.36	0.01±0.01
$D\bar{D}$	0.73	4.14	11.44±4.42
$D_s\bar{D}_s$	3.73	0.49	7.55±2.97
$\eta\eta_c$	1.97	0.98	0.12±0.09

Table 6: Residues for the poles in the C=0, S=0, I=0 sector

Channel	Chiral model (GeV)	Phenom. model (GeV)
DK	10.21	9.08±2.53
$D_s\eta$	6.40	5.25±1.43
$D_s\eta_c$	0.48	1.45±0.47

Table 9: Residues for the $D^*_{s0}(2317)$ pole

Channel	Chiral model (GeV)	Phenom. model (GeV)
$D\pi$	8.91	11.31±0.78
$D\eta$	1.36	3.46±0.27
$D_s\bar{K}$	5.71	8.58±0.32
$D\eta_c$	3.20	2.20±0.18

Table 10: Residues for the $D^*_0(2400)$ pole.

Axial vector mesons with charm and hidden charm

D. Gamermann, E. O, Eur. Phys. J. A.

Interaction of pseudoscalar mesons with vector mesons

$$\mathcal{L} = \frac{-1}{4f^2} Tr\left(J_\mu \mathcal{J}^\mu\right)$$

$$\begin{aligned} J_\mu &= (\partial_\mu \Phi)\Phi - \Phi\partial_\mu \Phi \\ \mathcal{J}_\mu &= (\partial_\mu \mathcal{V}_\nu)\mathcal{V}^\nu - \mathcal{V}_\nu \partial_\mu \mathcal{V}^\nu \end{aligned}$$

$$\begin{pmatrix} \frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} + \frac{J/\psi_\mu}{\sqrt{12}} & \rho^+_\mu & K^{*+}_\mu & \bar{D}^{*0}_\mu \\ \rho^{*-}_\mu & \frac{-\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} + \frac{J/\psi_\mu}{\sqrt{12}} & K^{*0}_\mu & D^{*-}_\mu \\ K^{*-}_\mu & \bar{K}^{*0}_\mu & \frac{-2\omega_\mu}{\sqrt{6}} + \frac{J/\psi_\mu}{\sqrt{12}} & D^{*-}_{s\mu} \\ D^{*0}_\mu & D^{*+}_\mu & D^{*+}_{s\mu} & \frac{-3J/\psi_\mu}{\sqrt{12}} \end{pmatrix}$$

The terms involving the exchange of charmed vectors are suppressed by the ratios of masses squared, as in the case of the interaction of pseudoscalar mesons.

This sector also studied by Kolomeitsev et al
and Chiang et al., exchanging only light vectors mesons

$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{-1}{4f^2}\Big(Tr\Big(J_{88\mu}\mathcal{J}^{\mu}_{88} + J_{3\bar{3}\mu}\mathcal{J}^{\mu}_{3\bar{3}} + J_{88_\mu}\mathcal{J}^{\mu}_{3\bar{3}} + J_{3\bar{3}\mu}\mathcal{J}^{\mu}_{88} + \gamma J_{83\mu}\mathcal{J}^{\mu}_{\bar{3}8} + \\
& \frac{2\gamma}{\sqrt{3}}(J_{83\mu}\mathcal{J}^{\mu}_{\bar{3}1} + J_{13\mu}\mathcal{J}^{\mu}_{\bar{3}8}) + \frac{4\gamma}{3}J_{13\mu}\mathcal{J}^{\mu}_{\bar{3}1}\Big) + \psi J_{\bar{3}3\mu}\mathcal{J}^{\mu}_{\bar{3}3} + \\
& \gamma J_{\bar{3}8\mu}\mathcal{J}^{\mu}_{83} + \frac{2\gamma}{\sqrt{3}}(J_{\bar{3}8\mu}\mathcal{J}^{\mu}_{13} + J_{\bar{3}1\mu}\mathcal{J}^{\mu}_{83}) + \frac{4\gamma}{3}J_{\bar{3}1\mu}\mathcal{J}^{\mu}_{13}\Big),
\end{aligned}
$$

with $\gamma = \left(\frac{m_L}{m_H}\right)^2$ and $\psi = -\frac{1}{3} + \frac{4}{3}\left(\frac{m_L}{m'_H}\right)^2$.

$$\mathcal{M}_{ij}^{C}(s,t,u) = \frac{-\xi_{ij}^{C}}{4f^2}(s-u)\epsilon.\epsilon'.$$

This kernel projected over s-wave and used as kernel
In the Bethe Salpeter equation.

Charm	Strangeness	$I^G(J^{PC})$	Channels
1	1	$1(1^+)$	πD_s^*, $D_s\rho$ KD^*, DK^*
		$0(1^+)$	DK^*, KD^*, ηD_s^* $D_s\omega$, $\eta_c D_s^*$, $D_s J/\psi$
	0	$\frac{1}{2}(1^+)$	πD^*, $D\rho$, KD_s^*, $D_s K^*$ ηD^*, $D\omega$, $\eta_c D^*$, DJ/ψ
	-1	$0(1^+)$	DK^*, KD^*
0	1	$\frac{1}{2}(1^+)$	πK^*, $K\rho$, ηK^*, $K\omega$ $\bar{D}D_s^*$, $D_s\bar{D}^*$, KJ/ψ, $\eta_c K^*$
	0	$1^+(1^{+-})$	$\frac{1}{\sqrt{2}}(\bar{K}K^* + c.c.)$, $\pi\omega$, $\eta\rho$ $\frac{1}{\sqrt{2}}(\bar{D}D^* + c.c.)$, $\eta_c\rho$, $\pi J/\psi$
		$1^-(1^{++})$	$\pi\rho$, $\frac{1}{\sqrt{2}}(\bar{K}K^* - c.c.)$, $\frac{1}{\sqrt{2}}(\bar{D}D^* - c.c.)$
		$0^+(1^{++})$	$\frac{1}{\sqrt{2}}(\bar{K}K^* + c.c.)$, $\frac{1}{\sqrt{2}}(\bar{D}D^* + c.c.)$, $\frac{1}{\sqrt{2}}(\bar{D}_s D_s^* - c.c.)$
		$0^-(1^{+-})$	$\pi\rho$, $\eta\omega$, $\frac{1}{\sqrt{2}}(\bar{D}D^* - c.c.)$, $\eta_c\omega$ $\eta J/\psi$, $\frac{1}{\sqrt{2}}(\bar{D}_s D_s^* + c.c.)$, $\frac{1}{\sqrt{2}}(\bar{K}K^* - c.c.)$, $\eta_c J/\psi$

C	Irrep Mass (MeV)	S	$I^G(J^{PC})$	RE($\sqrt{s}$) (MeV)	IM($\sqrt{s}$) (MeV)	Resonance ID
1	$\bar{3}$ 2432.63	1	$0(1^+)$	2455.91	0	$D_{s1}(2460)$
		0	$\frac{1}{2}(1^+)$	2311.24	-115.68	$D_1(2430)$
	6 2532.57 -i199.36	1	$1(1^+)$	2529.30	-238.56	(?)
		0	$\frac{1}{2}(1^+)$	Cusp (2607)	Broad	(?)
		-1	$0(1^+)$	Cusp (2503)	Broad	(?)
	$\bar{3}$ 2535.07 -i0.08	1	$0(1^+)$	2573.62	-0.07 [-0.07]	$D_{s1}(2536)$
		0	$\frac{1}{2}(1^+)$	2526.47	-0.08 [-13]	$D_1(2420)$
	6 Cusp (2700) Narrow	1	$1(1^+)$	2756.52	-32.95 [cusp]	(?)
		0	$\frac{1}{2}(1^+)$	2750.22	-99.91 [-101]	(?)
		-1	$0(1^+)$	2756.08	-2.15 [-92]	(?)
0	1 1055.77	0	$0^-(1^{+-})$	925.12	-24.61	$h_1(1170)$
	8 1161.06	1	$\frac{1}{2}(1^+)$	1101.72	-56.27	$K_1(1270)$
		0	$1^+(1^{+-})$	1230.15	-47.02	$b_1(1235)$
			$0^-(1^{+-})$	1213.00	-5.67	$h_1(1380)$
	1 3867.59	0	$0^+(1^{++})$	3837.57	-0.00	$X(3872)$
	8 1161.37	1	$\frac{1}{2}(1^+)$	1213.20	-0.89	$K_1(1270)$
		0	$1^-(1^{++})$	1012.95	-89.77	$a_1(1260)$
			$0^+(1^{++})$	1292.96	0	$f_1(1285)$
	1 3864.62 -i0.00	0	$0^-(1^{+-})$	3840.69	-1.60	(?)

RESULTS

Results in brackets When considering finite width of ρ and K* mesons

Hidden charm predicted states. They are nearly degenerate but with opposite C-parity.

K.Terasaki, 07
also advocates for two different C-parity states

Argument in favour of the two C-parity hidden charm axial vectors

Three pions seen in an ω state
Total C-parity positive

The large branching fraction

$$\frac{B(X \to \pi^+\pi^-\pi^0 J/\psi)}{B(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3 \quad (27)$$

reported in [47] indicates a massive violation of G-parity and hence isospin if one has only one X particle.

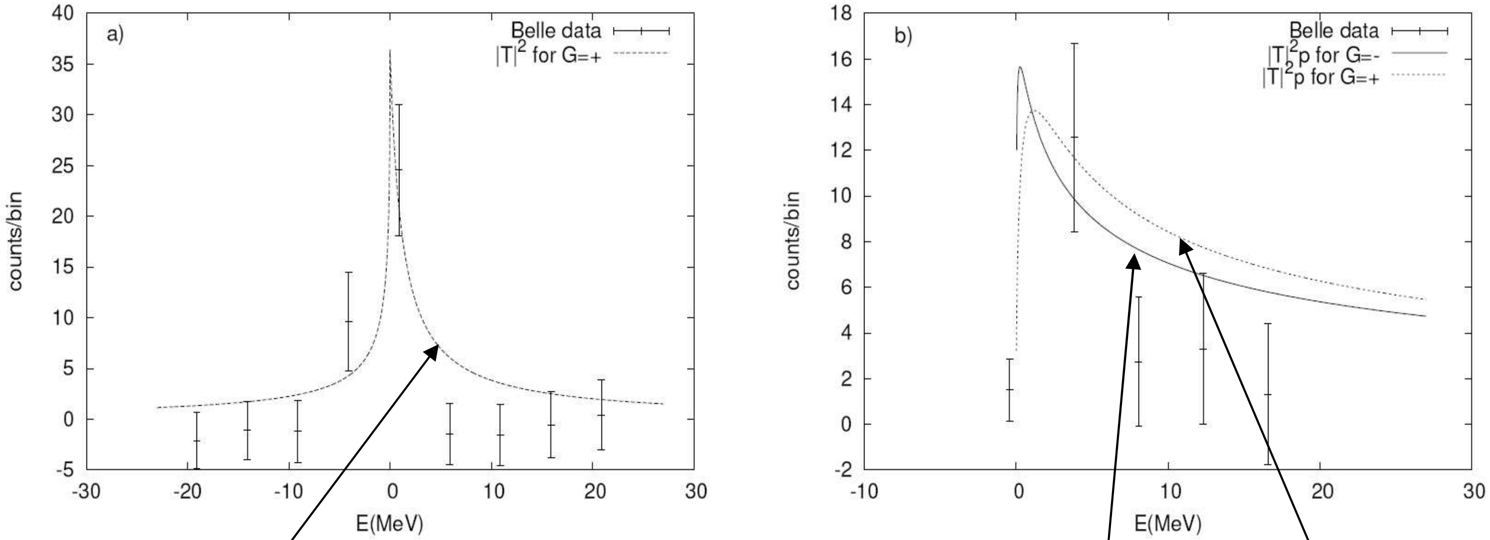
There is a more appealing explanation for eq. (27) if one had two $X(3872)$ states with different G-parity and correspondingly C-parity. Should the $\pi^+\pi^-$ in the denominator of eq. (27) correspond to an I=0 state one would not have to invoke isospin violation, but instead the existence of a negative G-parity (and hence C-parity) state. This would imply that there is strength of these events in the σ region of the $\pi\pi$ invariant mass, and this seems to be the case as reported in [27], although

Strength seen for the two pions in the sigma region

[47] K. Abe *et al.*, arXiv:hep-ex/0505037.

[27] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D 71, 071103 (2005)

a)



b)

C-par +

$$\frac{dBr_+}{dE} \propto |T(\bar{D}^0 D^{0*} + c.c. \to \bar{D}^0 D^{0*} + c.c.)|^2 \Gamma(X \to \pi^+\pi^- J/\psi)$$

Exp. reported by BELLE as evidence of new state X(2875)

C-par -

$$\frac{dBr_-}{dE} \propto |T(\bar{D}^0 D^{0*} - c.c. \to \bar{D}^0 D^{0*} - c.c.)|^2 \Gamma(X' \to \bar{D}^0 D^{0*})$$

C-par +

$$\frac{dBr_-}{dE} \propto |T(\bar{D}^0 D^{0*} + c.c. \to \bar{D}^0 D^{0*} + c.c.)|^2 \Gamma(X' \to \bar{D}^0 D^{0*})$$

Option of Hanhart et al 07

Figure 2: a)$|T|^2$ for the positive G-parity state in the $D\bar{D}^*$ channel compared with the Belle Data (in this plot $\alpha_H = -1.23$) b) $|T|^2p$ for both G-parity states in the $D\bar{D}^*$ channel compared with the Belle Data (in this plot $\alpha_H = -1.30$ for the G=- state)

C	S	$I^G(J^{PC})$	$Re(\sqrt{s})$ (MeV)	$Im(\sqrt{s})$ (MeV)	Channel
1	1	$1(1^+)$	2529.30	-238.56	πD_s^*, KD^*
1	0	$\frac{1}{2}(1^+)$	Cusp (2607)	Broad	-
1	-1	$0(1^+)$	Cusp (2503)	Broad	-
1	1	$1(1^+)$	2756.52	-32.95 [cusp]	$D_s\rho$, DK^*
1	0	$\frac{1}{2}(1^+)$	2750.22	-99.91 [-101]	$D\omega$
1	-1	$0(1^+)$	2756.08	-2.15 [-92]	$D\bar{K}^*$
0	0	$0^-(1^{+-})$	3840.69	-1.60	$\eta_c\omega$, $\eta J/\psi$

Table 13: List of predicted and not yet observed resonances with quantum numbers and the open channels to which they couple most strongly. The results in brackets for the $Im\sqrt{s}$ are obtained taking into account the finite width of the ρ and K^* mesons.

Conclusions

- The chiral unitary approach, combining chiral dynamics with the unitarity in coupled channels, has proved very efficient describing the interaction of hadrons and the generation of some resonances.

- Some scalar mesons with open and hidden charm are generated dynamically. Some correspond to known states and others are predictions for new ones.

- Some axial vector resonances with charm and hidden charm are predicted. Some correspond to known states and othersare predictions for new ones.

- The sectors with hidden charm and with no charmed mesons barely couple.

- Two hidden charm states X(3872) states are found with different C-parity.

- Experimental data needed to test the new states predicted